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Interim Technical Report
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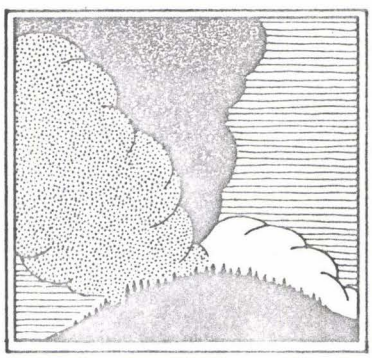

DIVISION OF FIRE RESEARCH
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REMARKS ON ESTIMATION OF THE NUMBER OF FIRES DUE TO IGNITION OF TRANSIENT EXTERIOR KINDLING FUELS

By

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Interim Technical Report AFSWP-861
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ABSTRACT

The problem of estimating the number of fires, during nuclear attack, due to ignition of transient exterior kindling fuels is discussed, and the behavior of ignition points in starting continuing fires is formulated. Mathematical expressions for determination of the number of fires per unit area originating from this fuel classification are developed which lead to the specification of rational experimental and survey programs.

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INTRODUCTION

The degree of fire damage, during nuclear attack, to urban and industrial areas and to military installations is directly related to the number of fire starts due to primary and secondary sources of ignition. The rate of fire build-up and subsequent fire behavior, the description of which must be known to establish rational fire suppression tactics, is also affected by the number and relative spacing of fire starts. One major source of primary fires, excluding by definition fire spread from structure to structure, is that fire which originates due to ignition of interior or exterior kindling fuel.

The problem then arises as to the evaluation of the number of fires started by kindling fuels as these data must be determined, per se, before they can be integrated into the over-all fire picture. The relationship between interior ignitions and interior fire starts is believed fairly well established from everyday fire experience. A survey and analysis method is at present being developed (1)[1/] for interior kindling fuels. Exterior fuels present, however, a more obtuse problem in that they are generally transitory in nature; also knowledge of their behavior as fire initiators is extremely meager.

A survey of exterior kindling fuels has been made (2) and the resulting data applied to analysis of urban targets (3). Results of the exterior fuel survey indicate an extraordinary number of ignition points (15,000 per sq.mi.) in certain areas, leading to the insinuation of a commensurate number of fire starts from this cause alone. A considerable reduction in the number of ignition points will result from proper evaluation of the probability of ignition, a problem which is currently being worked upon.

There is in addition, however, a problem in the formulation of the behavior of transient exterior kindling fuels in causing primary fires.

1/ Underlined numbers in parentheses refer to Literature Cited, page 19.

The purpose of this analysis is to consider this problem in a very general manner so as to provide a basis for further experimentation and survey analysis. The complexities are retained throughout the analysis so that one may clearly see what assumptions are necessary in order that the computation of the number of primary fires be feasible and also, perhaps more important, to see the result of various previously made assumptions (2).

THEORETICAL ANALYSIS

Before proceeding with the analysis it is appropriate to define the basic elements of the problem and describe the supposed behavior of an ignition point in starting a continuing fire. The fuel unit is the primary fuel element, as previously described.2/ The quantity of fuel contained in a fuel unit remains arbitrary. However, this amount should, for practical reasons, be neither too large nor too small. An ignition point is a fuel unit adjacent to a combustible structure multiplied by its probability of ignition.2/ A fuel concentration contains several fuel units in close contact such that mutual interaction exists between their ignitions.

A rational assumption is that all fuel concentrations will not have equal probability of starting a fire in a structure depending on the number of fuel units contained, the arrangement of the concentration and structure, and the type of structure. Neither is there reason to expect a linear relationship between the probability of starting a continuing fire and the number of fuel units per fuel concentration. These data can be determined independently by experiment of target fuel surveys.

A second postulate is randomness of fuel concentrations with respect to time and space. If this is assumed then one may consider the diurnal translations of the transient kindling fuels to be one of

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2/ See (2), pp. 12 and 13.

steady state, i.e., the same amount of fuel is moving toward combustible structures as away. Hence, a fuel concentration containing a given number of fuel units appears with a fixed frequency of occurrence which may be determined by a fuel survey. The hypothesis as to the consistency of the frequency of occurrence must be proven by repeated surveys of the same area and is, in fact, a measure of the adequateness of the sample size.

Fuel concentrations adjacent to all structures, whether combustible structures or not, are counted since the analysis corrects this count by statistical means. Fuels not adjacent to structures constitute a reservoir from which fuels continually migrate; however, these fuel concentrations are not counted since their probability of starting a fire is zero in their present position. The action of blast winds on these fuels is an open question. Until further information is obtained on this point, the steady state hypothesis must be adopted, i.e., blast moves as many fuels away from favorable positions as it moves into these positions.

With this general description in mind, the problem may be translated into mathematical terms.[3/] Consider a number of fuel classifications i (where $i = 1, 2, 3 \ldots n$) and a number of structure classifications j (where $j = 1, 2, 3 \ldots m$) which describe the fuels and structures under investigation. Both fuel and structures are considered to be distributed along a street which is assumed typical of the area under consideration.

Let q be the number of fuel units per fuel concentration. For a type j structure, a type i fuel concentration containing q fuel units has the probability of starting a continuing fire $P_{ij}(q)$, as illustrated in figure 1 (page 15). In general there will be $n(m-1)$ curves since one structure type will be noncombustible, i.e., $P_{ij} \equiv 0$ for all fuel combinations with noncombustible structures.

3/ See page 17 for Nomenclature.

In the establishment of such curves the definition (quantity) of a fuel unit may play an important role in determining the number of fuel-structure combinations and hence the number of curves that must be considered. The feasibility of such a study is in geometric proportion to the number of fuel types, n, and the number of structure types, m, which must be analyzed. The importance of reducing the number of variables is easily recognized when one considers that for $m = n = 4$ there are 12 combinations, for $m = n = 3$ there are only 6 combinations, etc.

Consider for a moment one fuel type i and one structure type j.

If the per cent of the total number of fuel concentrations of fuel type i is b_i then

$$N_i = \frac{\text{no. of type i fuel concentrations adjacent to all structures}}{\text{unit length of building circumference}} = N_c b_i \quad (1)$$

where $$N_c = \frac{\text{no. of all fuel concentrations adjacent to all structures}}{\text{unit length of building circumference}}$$

Basing the number of fuel concentrations on length of building circumference is an arbitrary procedure and is subject to modification when survey results indicate the correct normalizing factor. Normalization of the number of fuel concentrations is, in fact, necessary in order to establish, statistically, the validity of fuel survey results and to effect comparison between urban use classifications (2). The base so chosen does not invalidate the remainder of the analysis provided b_j, equation (6), is normalized accordingly. Change of base will appear as a base change in the definition of $F_L(w)$, equation (14), and subsequent equations.

Each type i fuel concentration containing between q and $q+dq$ fuel units (the differential class interval dq) appears with a frequency $f_i(q)$. The interpretation of this frequency may be recognized from the integral definition of the cumulative distribution function

$$\int_o^q f_i(q)dq = F_i(q) \quad (2)$$

or $$f_i(q) = \frac{d\left[F_i(q)\right]}{dq} \tag{3}$$

where $F_i(q)$ is the per cent of fuel concentrations which contain q or less number of fuel units. Since q must be counted in finite steps, the frequency of occurrence, $f_i(q)$ may best be found from differentiation of the cumulative curve. The number of fuel concentrations per unit length of building circumference containing q fuel units in the class interval dq is then

$$N_i(q) = N_c b_i \, d\left[F_i(q)\right] = N_c b_i \, f_i(q) \, dq \tag{4}$$

The number of fuel units in this interval is then

$$N_c b_i \, f_i(q) \, q \, dq \tag{5}$$

The per cent of building circumference occupied by j is b_j. The probability that type j structure will appear in conjunction with a type i fuel concentration containing q fuel units in the interval dq is the product of the probability of occurrence of the structure and the probability of occurrence of the fuel

$$b_j \cdot \frac{N_i(q)}{N_c} = b_j \, b_i f_i(q) \, dq \tag{6}$$

The number of fuel-structure combinations containing q fuel units per unit length of building circumference is the total number of fuel concentrations times the probability of occurrence of the fuel-structure combination

$$N_c \, b_j \, b_i f_i(q) \, dq \tag{7}$$

and the number of associated fuel units is

$$N_c \, b_j \, b_i f_i(q) \, q \, dq \tag{8}$$

The number of concentrations which will be ignited and be effective then will be the number of fuel-structure combinations times their probability of ignition. The probability of ignition, P_{ikw}, which depends on the fuel (i) ignition energy, orientation of fuel concentrations relative to surrounding buildings and topography (k), weapon yield and height of burst (w), will vary from concentration to

concentration. We must assume however that there exists an area subdivision or building orientation classification k (where $k = 1, 2, 3 \ldots r$) in which the postulated random behavior of fuels does not result in significant changes in probability of ignition so far as fuel orientation affects this probability.

At this location k, fuel parameters, by previous hypothesis, are invariant. There is however a possibility that fuel parameters will be biased by those particular building geometries which play an important role in the specification of the probability of ignition. For example, alleyways with a small seen sky area may accumulate a larger number of concentrations than open areas such as back yards. Hence provision must be made for this possibility by delineating fuel (and structure) parameters by providing an additional subscript k.

We have now prescribed a homogenous target, in which the number of fuel concentrations N_{ck}, the per cent of type i fuels b_{ik}, their frequency of occurrence $f_{ik}(q)$, their probability of ignition P_{ikw}, and the per cent of type j structures b_{jk} are considered as constants. The probability of the ij fuel-structure combination starting a continuing fire remains independent of the area k.

The number of concentrations ignited becomes

$$P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik}\, f_{ik}(q)\, dq \tag{9}$$

The number of primary fires is the number of ignited concentrations times the probability that a concentration will cause a primary fire

$$P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik}\, f_{ik}(q)\, P_{ij}(q)\, dq \tag{10}$$

The number of ignition points will be

$$P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik}\, f_{ik}(q)\, q\, dq \tag{11}$$

The total number of fires due to this i-j fuel-structure combination is the integral of equation (10) over all the intervals dq

$$P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^{\infty} f_{ik}(q)\, P_{ij}(q)\, dq \tag{12}$$

and the total number of ignition points is from equation (11)

$$P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}(q)\; q\; dq \tag{13}$$

The total number of fires per unit length of building circumference for a given yield and HOB $F_L(w)$ is found by summing over all classes i , j , and k

$$F_L(w) = \sum_{i=1}^{n} \sum_{j=1}^{m-1} \sum_{k=1}^{r} P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}(q)\; P_{ij}(q)\; dq \tag{14}$$

The number of fires per unit area is then

$$F_A(w) = \frac{L}{A} \sum_{i=1}^{n} \sum_{j=1}^{m-1} \sum_{k=1}^{r} P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}(q)\; P_{ij}(q)\; dq \tag{15}$$

where $\frac{L}{A}$ equals length of building circumference per unit area. Also

$$F_A(w) = \sum_{i=1}^{n} \sum_{j=1}^{m-1} \sum_{k=1}^{r} P_{ikw}\, N_{Ak}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}(q)\; P_{ij}(q)\; dq \tag{16}$$

where N_{Ak} equals the number of fuel concentrations per unit area.

The number of fires per ignition point, $F_I(w)$, is the total number of fires divided by the total number of ignition points

$$F_I(w) = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m-1} \sum_{k=1}^{r} P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}\, P_{ij}\, dq}{\sum_{i=1}^{n} \sum_{j=1}^{m-1} \sum_{k=1}^{r} P_{ikw}\, N_{ck}\, b_{jk}\, b_{ik} \int_0^\infty f_{ik}\, q\, dq} \tag{17}$$

If the frequency of fuel units per concentration, q , is normally distributed, then

$$\int_0^\infty f_i(q)\; q\; dq = \frac{\sigma}{\sqrt{2}} \left[2z + \text{ierfc}(z) \right] \tag{18}$$

where σ is the standard deviation of the frequency distribution
$\bar{q}$ = the mean value
$z = \bar{q}/\sigma\sqrt{2}$

For $z > 1.45$

$$\int_0^\infty f_i(q)\ q\ dq \cong \bar{q} \text{ (less than 1 per cent error)} \qquad (19)$$

DISCUSSION

The analysis does not consider cross-products of fuel concentrations, as their probability of occurrence is of second order. Each concentration is assumed to act independent of any other as far as the efficiency in starting a continuing fire; however, fuel units within a concentration are not assumed independent. This is the major difference, aside from considering different fuels-structure combinations, between this and previous analyses.

The non-independency of fuel units within a fuel concentration, i.e., $\int f_i(q)\ P_{ij}(q)\ dq$, is the major factor in reducing the number of fires from the number found under the assumption that all fuel units act independently, i.e., $P_{ij}(q) \equiv 1$. For $P_{ij}(q) \equiv 1$ the integral

$$\int_0^\infty f_i(q)\ P_{ij}(q)\ dq \equiv 1$$

For $P_{ij}(q) < 1$ then

$$\int_0^\infty f_i(q)\ P_{ij}(q)\ dq < 1$$

and may be very small if the frequency distribution is out of phase with the probability of starting a fire.

This may best be illustrated by a numerical example. Assume that a hypothetical fuel has the probability of starting a continuing fire as shown in figure 1, and is distributed in three separate cases as shown in figure 2.[4/] Further assume that only one combustible structure type (m=2) and only a single fuel type (n=1) are present. Equation (17) then becomes, simply

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4/ The probabilities of figures 1 and 2 are shown normally distributed. This assumption pertains only to the illustrative example and does not limit the generality of equations (14) through (17).

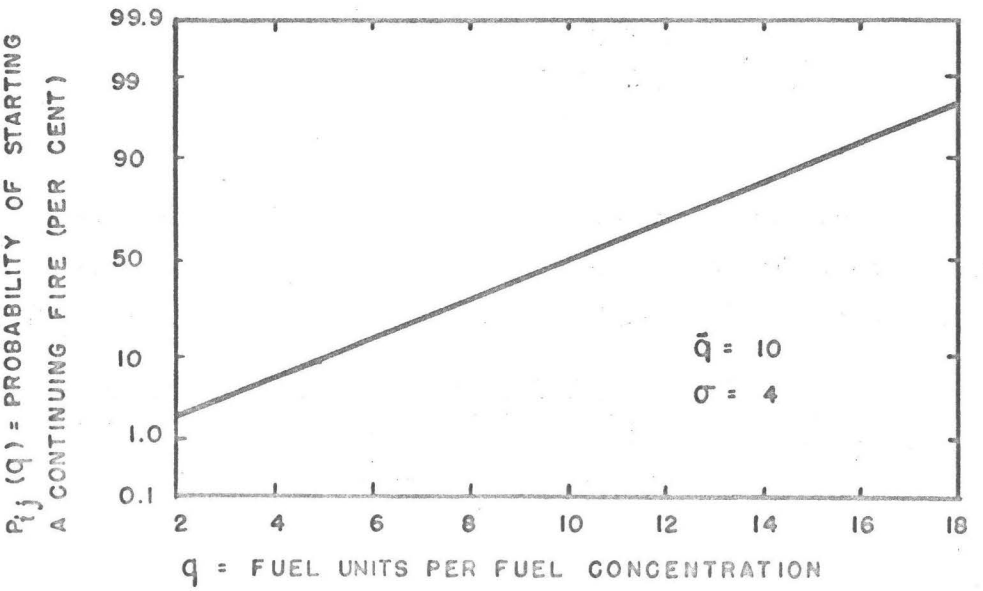

Figure 1.- The probability of a fuel (i) starting a continuing fire in a structure (j). Illustrative example ($\bar{q}$ is the mean and σ the standard deviation).

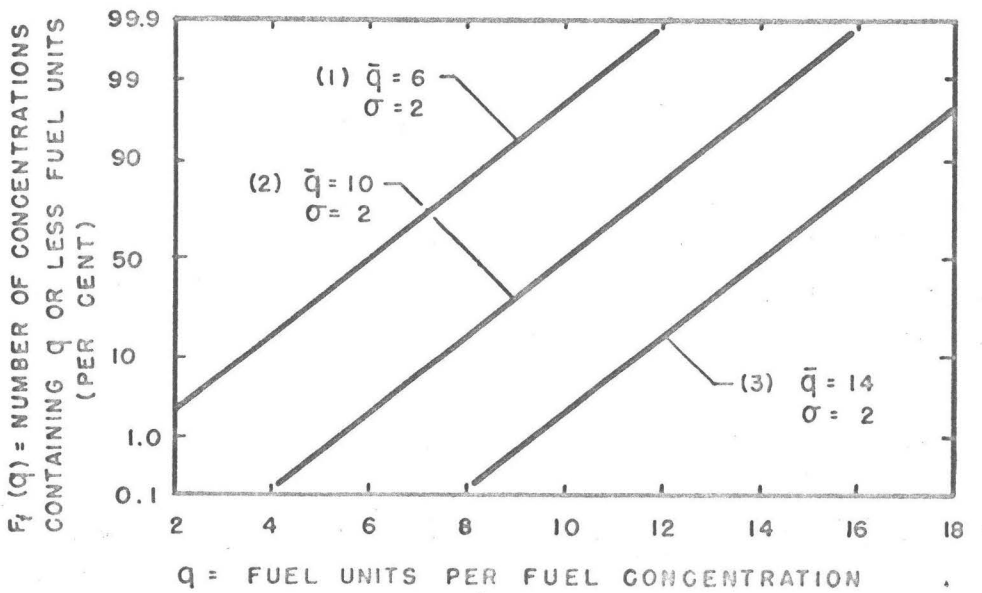

Figure 2.- The cumulative distribution function for three hypothetical fuels. Illustrative example ($\bar{q}$ is the mean and σ the standard deviation).

$$F_I(w) = \frac{\int_0^\infty f\ P\ dq}{\int_0^\infty f\ q\ dq}$$

A summary of results for these fuel-structure combinations is displayed in Table 1. For this example the minimum number of ignition points per fire is 16-1/2 since, in the limit, as $\bar{q} \to \infty$ then $F_I \to 1/\bar{q}$.

Table 1.- Summary of results for hypothetical fuel

Case (figure 2)	1	2	3
$\bar{q}$	6.0	10.0	14.0
σ	2.0	2.0	2.0
$\int_0^\infty f\ P\ dq$	0.184	0.496	0.819
$\int_0^\infty f\ q\ dq$	6.0	10.0	14.0
$F_I(w,k)$	0.0307	0.0496	0.0585
Ignition points per fire	33	20	17

CONCLUSIONS

It has been shown that if a single fuel unit is assumed to have less than unit probability in starting a continuing fire then the relative value of the mean number of fuel units per fuel concentration, with respect to the average number of fuel units required to start a fire, has considerable influence in determining the number of fires to be expected.

Until the basic experiments which will produce the $P_{ij}(q)$ and the $f_i(q)$ curves are performed, the problem will remain hypothetical, and estimation of even an approximation to the number of fires per unit area is impossible.

NOMENCLATURE

b_i = per cent of total number of fuel concentrations of fuel type i .

b_{ik} = per cent of total number of fuel concentrations of fuel type i at location k .

b_j = per cent of building circumference occupied by structure type j .

b_{jk} = per cent of building circumference occupied by structure type j at location k .

$f_i(q)$ = frequency of occurrence of a type i fuel concentration containing q fuel units.

$f_{ik}(q)$ = frequency of occurrence of a type i fuel concentration containing q fuel units at location k .

$F_i(q)$ = cumulative distribution function; the per cent of fuel concentrations which contain q or less number of fuel units.

$F_A(w)$ = number of fires due to exterior ignitions per unit area for weapon w .

$F_I(w)$ = number of fires due to exterior ignitions per ignition point for weapon w .

$F_L(w)$ = number of fires due to exterior ignitions per unit length of building circumference for weapon w .

m = total number of structure types considered, including noncombustible structures.

n = total number of fuel types considered.

N_c = number of fuel concentrations adjacent to all structures per unit length of building circumference.

N_{ck} = number of fuel concentrations adjacent to all structures per unit length of building circumference at location k .

N_i = number of type i fuel concentrations adjacent to all structures per unit length of building circumference.

N_{Ak} = number of fuel concentrations adjacent to all structures per unit area at location k .

P_{ikw} = probability that a type i fuel concentration will be ignited at location k by a nuclear explosion of yield and HOB w .

$P_{ij}(q)$ = probability that a type i fuel concentration containing q fuel units will start a primary fire in a type j structure.

q = number of fuel units per fuel concentration.

$\bar{q}$ = average number of fuel units per fuel concentration.

r = total number of location classifications considered.

z = $\bar{q}/\sigma\sqrt{2}$

σ = the standard deviation of the frequency distribution.

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